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Indexing Current Watershed Conditions Using Remote Sensing and GIS

ABSTRACT

Two objectives of the Sierra Nevada Ecosystem Project (SNEP) were to evaluate the current condition of watersheds in the Sierra Nevada and to identify physical processes such as soil erosion that affect watershed health and sustainability. In response to this request for a resource inventory, an indexing or screening model has been developed that produces both a natural erosion potential (NEP) and sedimentation hazard index (SHI), which are indicators of the current cumulative condition in watersheds of the Sierra Nevada.

The goal of the study undertaken here is to design and test a methodology using geographic information systems (GIS) and remote sensing to rank watersheds prone to soil erosion and locate specific sites where stream sedimentation is likely to occur. One hundred and thirty-four watersheds on the Eldorado National Forest (ENF) were analyzed and ranked using a method that selects the parameters of slope, cover, and soil detachability, which were assumed to be the most significant contributors to soil erosion, given uniform climatic conditions. Threshold values established for these parameters provided the link to locations where there is a high probability of sediment reaching the watercourse.

Correlation with U.S. Forest Service equivalent roaded acres (ERA) and cumulative watershed effects (CWE) work previously completed and in progress on the ENF was positive when compared to NEP and SHI rankings created by this model. Additional correlation opportunities yet to be implemented using change detection techniques with Landsat TM imagery, spectral mixture analysis (SMA) with high resolution AVIRIS imagery, and the identification of large rock outcrops are expected to improve results. The model described here gives the resource manager a tool that can be used to quickly screen proposed CWE assessment areas and focus both human and financial resources on potential "hot spots." Once located, the cumulative effects benefit of a specific mitigation opportunity may be evaluated as to its cost and to the watershed improvement that it provides.

INTRODUCTION

Two objectives given to the Sierra Nevada Ecosystem Project were to evaluate the current condition of watersheds in the Sierra and to identify physical processes such as soil erosion that affect watershed health and sustainability. The goal of this project was to utilize geographic information systems and remote sensing as the basis of a watershed assessment model. This model ranks watersheds prone to soil erosion and locates specific sites where stream sedimentation is likely to occur.

A healthy watershed is defined here as an area of land having the structure and density of vegetative stands to support a diverse wildlife population and having the natural stability of geology and soils to maintain the contribution of eroded sediments reaching streams at a level where natural hydrologic processes balance the ability of the system to both store and transport these sediments without degrading aquatic habitats. One hundred and thirty-four Cal-Water planning watersheds on the Eldorado National Forest (ENF) were analyzed and ranked using a method that selects three physical landscape parameters most likely to contribute to soil erosion: slope, surface cover, and soil erosivity or detachability. Threshold values established for these parameters provided the link to locations with high probability of sediment reaching a watercourse.

Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources, 1996.

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Resource managers need practical tools for watershed assessment. Those tools should be based on simple concepts and built around readily available or easily acquired information. The method proposed here requires the user to have access to Landsat imagery and a limited knowledge of soils, geomorphology, and ecology. Doing hierarchical analysis, first using a screening tool followed by more data-intensive and quantitative procedures, allows managers to identify and prioritize both analytical and restoration activities. This model gives the resource manager a tool that may be used to quickly screen proposed cumulative watershed effects assessment areas and focus both human and financial resources on potential "hot spots." Once located, the cumulative effects benefit of a specific mitigation opportunity may be evaluated relative to its cost versus the environmental watershed improvement that it provides. Figure 54.1 locates the Eldorado National Forest relative to SNEP's regional study area (see inset) and identifies specific drainages such as Fry Creek and Camp Creek.

Regional Background

Years of grazing, mining, road building, home construction, and logging disturbances as well as fire, landslides, and plant disease have modified forest ecosystems in the Sierra Nevada. Present remote sensing technology provides for observing, measuring, and monitoring natural and management-induced changes such as soil loss, vegetative cover, and habitat disturbance. There are, however, very few predictive ecosystem models that use spatial and temporal remote sensing data to infer cumulative watershed condition or ecosystem health. Comparison of current condition on a watershed-by-watershed basis allows us to index ecosystems relative to each other. An accurate indexing methodology is a valuable tool when allocating resources for cumulative watershed effects (CWE), mitigation, or adjudicating disturbance rights among landowners in mixed ownership watersheds.

The methodology presented here assesses the ecosystem, as defined by watershed boundaries, for natural erosion potential and sedimentation hazards. It suggests physical parameters for ecosystem assessment and an accounting system to track and recalculate a watershed condition index. Data on these parameters—that is, amount of ground cover, bare soil, soil detachability, or sensitivity to erosion as well as slope—are used to quantify the ecosystem's sensitivity to accelerated erosion and sedimentation. Geographic information system (GIS) layers of slope, soil type, soil detachability, disturbance history data, and road and stream proximity are integrated to spatially display current relative watershed condition.

Both national and state environmental quality acts (NEPA and CEQA) require cumulative effects assessment for all land disturbance "projects" on private, state, and federal land. Definitions of cumulative effects vary, and there are no universally accepted techniques for their measurement or monitoring. Our inability to objectively quantify cumulative effects and the absence of standards for comparison have created difficulty for regulatory agencies. This model aids resource managers and agency regulators in objectively analyzing ecosystem complexities with particular regard for cumulative and synergistic impacts of human activity and natural processes.

With the advent of GIS technology, spatial analysis procedures are available to quantify both present and historic physical features and land-use practices on a landscape basis. From the rates of change in these features, as determined by GIS interpretations of aerial and space imagery, habitat improvement or degradation and habitat potential may be inferred. Simultaneous analysis of several GIS layers provides a more objective view of ecosystem condition.

METHODS

Model Description

The model produces a natural erosion potential (NEP) and sedimentation hazard index (SHI) as indicators of the "current cumulative condition" in the watershed. Watershed characteristics used to assess relative health include an estimate of natural sensitivity to erosion, and an analysis of the location and number of roads, to allow prediction of probable origins of sediment. Because this present model is a screening tool, it focuses on initial soil-forming and erosional processes. The susceptibility of soils and geology to mass failure and rill and gully erosion are part of this process.

GIS Methodology and Logic

The model is similar to pre-GIS geographic map overlaying techniques in which clear acetate sheets scribed with information at one spatial and temporal scale are overlaid by other maps with information from a different time period or a different spatial arrangement. In this system both of these sheets are fixed to a base map containing information such as topography, streams, and soils common to both overlays. In order to begin to understand the relationships between the aggregated information, we analyze the composite. New values may be constructed, or the data may be classified by forming statistically similar clusters, which are referred to as polygons, or if at single points, cells. Using a commercial grid GIS computer program, data are distributed over a matrix with 0.22-acre cells, with dimensions of 30 meters on each side. This fine scale allows large numbers of attribute variables such as soil, slope, and vegetation to be viewed individually or simultaneously in very rapid order for a single cell or a cluster of cells, speeding the analysis process. Every major attribute, soil, for instance, may have dozens or hundreds of variables that describe the soil at a specific location.

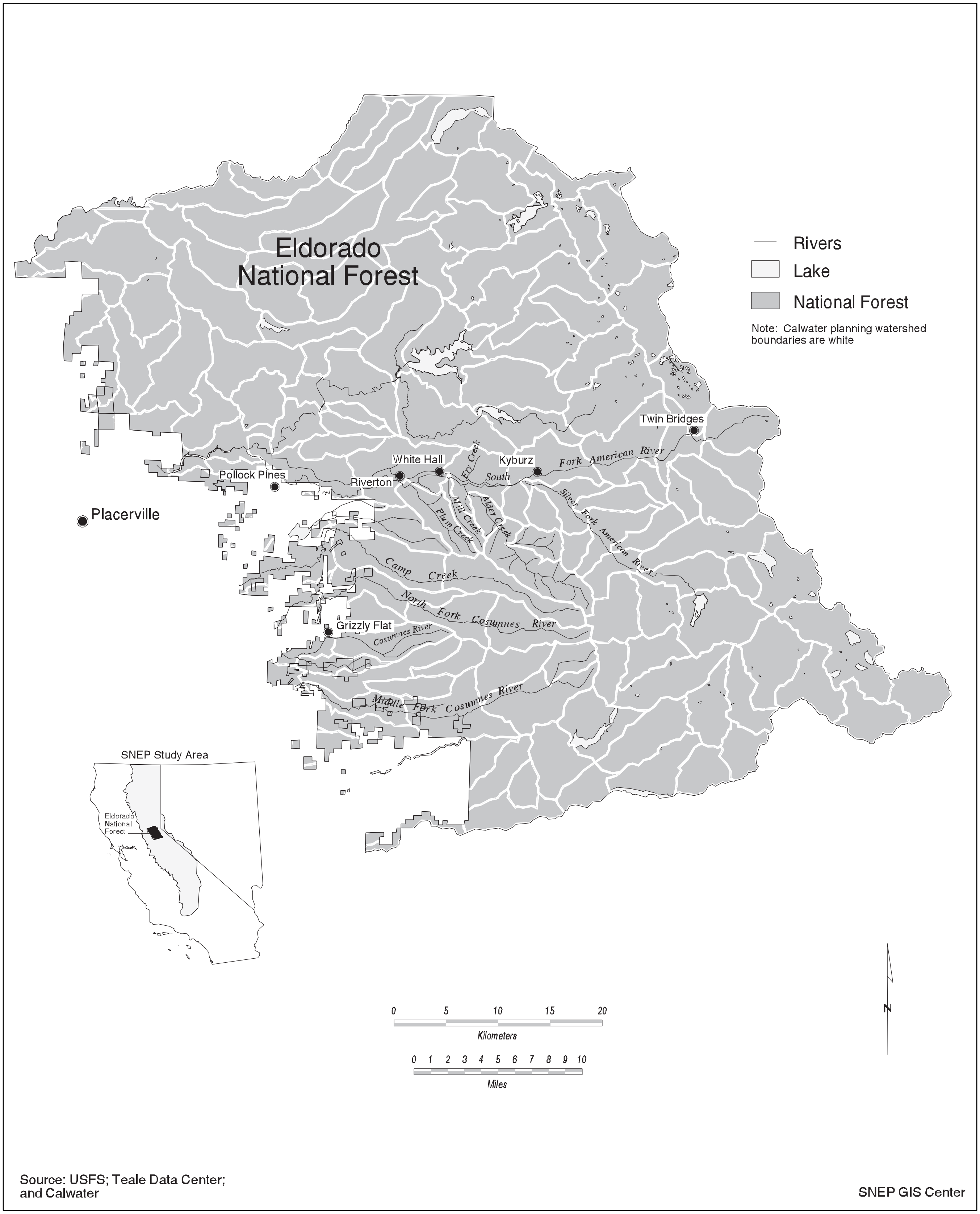

FIGURE 54.1

SNEP study area and Eldorado National Forest location map.

One database or many may support our understanding of a fixed point on the ground. GIS provides a means of mathematically searching for relationships between data layers and their attributes that might not be apparent to our eyes and may have been missed using earlier techniques.

Model Hypothesis

If a healthy watershed is determined by the degree to which physical processes and biological responses are at equilibrium, then excessive erosion and sedimentation suggest system instability and declining health. The hypothesis for this model is that risk of erosion is primarily a function of steep slopes, high soil detachability, and bare unprotected ground. Further, the risk of erosion becoming sedimentation increases where roads are close to streams and is decreased by the presence of a riparian vegetation buffer near stream banks. Slope; soil detachability, or K-factor; and ground cover become the three critical parameters of the models. Stream buffers are not a parameter but limit the area viewed by the sedimentation hazard index (SHI) model. Using the program ARC/INFO GRID as well as available soil and topography data, these parameters are plotted from GIS and Landsat Thematic Mapper (TM) satellite imagery.

Initial Parameter Thresholds

In order to rank watersheds for comparison, erosion and sedimentation hazard risks are quantified. Each of the above parameters is assigned a threshold value as described in the following section. These thresholds are indicators for potential erosion. Values for each watershed cell are determined by the number of thresholds—slope, cover, and detachability—exceeded within that cell. Given normal precipitation conditions for the central Sierra Nevada, it is assumed that each parameter or risk factor has about the same probability of causing erosion. The GIS does not count the cell until the parameter value in that cell exceeds an established threshold. Each time a parameter threshold is exceeded, a “1” is tabulated for that cell. A cell value may be 0, 1, 2, or 3, as seen in table 54.1, where the seven possible combinations of parameters and their corresponding values are displayed.

Threshold Values

Here risk thresholds are defined as slopes in excess of 40%, soils with K-factors (detachability ratings) higher than 0.28, and cells with more than 40% bare soil or no surface cover (Elwell and Stocking 1974). These threshold values were derived from the soil literature (Wischmeier and Smith 1978; Rose 1994; Stocking 1994), from current U.S. Forest Service limits for tractor and cable yarding, and from the California and Washington State Forest Practice rules. Along with the intensity of precipitation, these three parameters are dynamically interactive, with each contributing to “critical shear,” detachment, and transport of soil both individually and collectively. For example, bare, highly detachable soils are not as erodable at slopes of 0% to 5% as they are at 15% to 35%; and conversely, bare, steep slopes are not as erodable when soil textures have low detachability values, as is the case with clays, as they are when soils are highly detachable, as is the case with very fine sandy loams (Mitchell and Bubenzer 1980; Kirkby and Morgan 1980). As more experience is gained in using this model, other threshold values will be explored and the model further refined into a continuous scale. Further, we plan to extend the model to include influences of other external factors such as climate and elevation. Adding these factors will allow us to predict the potential for erosion following rain-on-snow events, thereby increasing the model’s sensitivity to natural and management changes.

This study used watershed boundaries mapped by the state of California’s Department of Forestry and Fire Protection in a data dictionary project known as “Cal-Water.” Cal-Water defines their smallest watershed unit as a planning watershed and gives it the acronym CWPWS, for Cal-Water planning watershed (Brandow 1995). Parameters exceeding threshold values have been quantified and analyzed for each CWPWS. These data will be used to provide a comparative index that, when examined along with the proximity of roads to streams and total area of disturbance, ranks watersheds by their areal percentage over threshold. The model calculates a current condition ranking on a “most-healthy to least-healthy” scale as judged by the percent of the watershed that exceeds each threshold or combination of thresholds.

TABLE 54.1

Maximum cell value calculation.

	Possible Combinations of Parameters over Threshold						
Parameter	**Slope**	**K-Factor**	**Cover**	**Slope + K-Factor**	**Cover + K-Factor**	**Slope + Cover**	**Slope + K-Factor + Cover**
Value	1	1	1	2	2	2	3

Soils Database and Derived Map Products

This analysis draws from three primary sources of information: slope is derived from a 30-meter digital elevation model (DEM) produced by the U.S. Geological Survey, bare ground is derived from a 1994 Landsat Thematic Mapper satellite image, and the soils information is found in four soil surveys from the Eldorado NF and the US Natural Resources Conservation Service (NRCS). Soils database attributes were derived from several sources of soil survey data such as engineering properties and physical/chemical properties. A number of products have resulted from this derived data. Plate 54.1 uses soil parent material and particular geologic formations to group soils that have similar erosion characteristics. This map provides foresters and resource managers with a ready reference of spatial information by basic geologic group and soil series.

Calculation of Natural Erosion Potential Percentage

Natural erosion potential (NEP) is an index of stability or resilience, predicting an unmanaged watershed's ability to withstand erosion causing events. As seen in plate 54.2 and table 54.2, this model operates on Boolean logic: when a cell's value exceeds any threshold, it is assigned an index value of 1; conversely, if the feature being assessed is less than the threshold, the cell value is assigned a value of 0. Cell value accuracy is a function of grid size. In the case of slope, using the best available information, which is the 30-by-30-meter DEMs, means that the angle formed using one cell's centroid elevation when compared to the centroid value of its neighbors either does or does not exceed the threshold. Each parameter has its own data layer in the GIS. Again referring to table 54.1, when two thresholds are exceeded for the same cell, the cell's value is the combination of those two data layers and has an index value of 2. Likewise, for the combination where all three thresholds are exceeded in the same cell, the value of that cell becomes 3. Therefore in the worst case (maximum NEP) every cell would have a value of 3. Multiplying three times the number of cells in a watershed yields the maximum potential NEP watershed value. The present watershed value is generated by counting the total number of cells over threshold in the composite GIS layers. The total values of cells exceeding thresholds, divided by the maximum potential for the watershed, times 100, becomes the relative watershed score or percentage NEP. The NEP for the whole national forest, graphically projected, is found in plate 54.2, where K-factor, bare ground, and slope have one column and the presence of a "1" indicates the parameter is over threshold. If a "1" is present in more than one column, it is interpreted as an increased erosion risk up to a value of 3. (See table 54.2 for further explanation.)

Using a computer monitor, plate 54.2 can be expanded so that individual 30-by-30-meter cells may be located and reviewed for soil, slope, or bare ground attributes. Even the very small scale displayed in this map provides sufficient spatially explicit information to make reasonable visual watershed comparisons and guide additional assessment work. Each watershed is given an attribute table that provides the user with specific information about those parameters being evaluated. These attribute tables on either a watershed or parameter scale may be accessed to add or edit data.

Plate 54.3 is the type of map that is used for field assessment work. It is the basis for the tables used to calculate the ranking of every cell and for aggregating up to planning watershed or river basin. Roads and stream buffers are shown so that areas of special concern may be reviewed for possible mitigation opportunities—for example, the Fry Creek watershed, shown in red and located in the upper center of plate 54.3. (Also see figure 54.1.)

Table 54.2 is an example of one of the data tables built for each watershed. The Interpretation column has been added for reader assistance. Cells over threshold and their corresponding acreages are summed at the bottoms of the columns. Values are not duplicated when thresholds are combined. Maps similar to the one in plate 54.3 were used in the field to validate the location of the soil and slope parameters and the percentage of bare ground estimated by the bare ground threshold. Both individual cells and clusters of cells were targeted and found for examination using a global positioning system (GPS).

Calculation of Sedimentation Hazard Index Percentage

Although NEP reflects a watershed's natural stability, SHI focuses on the potential to upset that stability through road construction and maintenance practices. Stream sedimentation is often the result of a very small erosional failure becoming a very large CWE disturbance (Megahan et al. 1991; Lewis and Rice 1989; Rice 1993). SHI seeks to evaluate detailed patterns in a stream buffer zone by identifying areas at risk, predicting specific points most likely to fail, and reflecting SHI reductions as road segments are abandoned, rocked, or paved.

As defined earlier, a healthy watershed is one in which the natural stability of geology and soils maintains the contribution of sediments at a level where natural hydrologic processes balance the ability of a system to both store and transport these sediments without degrading aquatic habitats. Assuming vegetation and debris in stream buffer zones can trap and stabilize incoming sediments, an adequate width for these buffers must be determined in order to protect habitats of aquatic and terrestrial species while permitting access to lands for management. Erman and colleagues (1977, 1983) looked at stream buffer widths and the impacts on benthic organisms. They found the population count and species diversity of these organisms were indicators of the condition of the

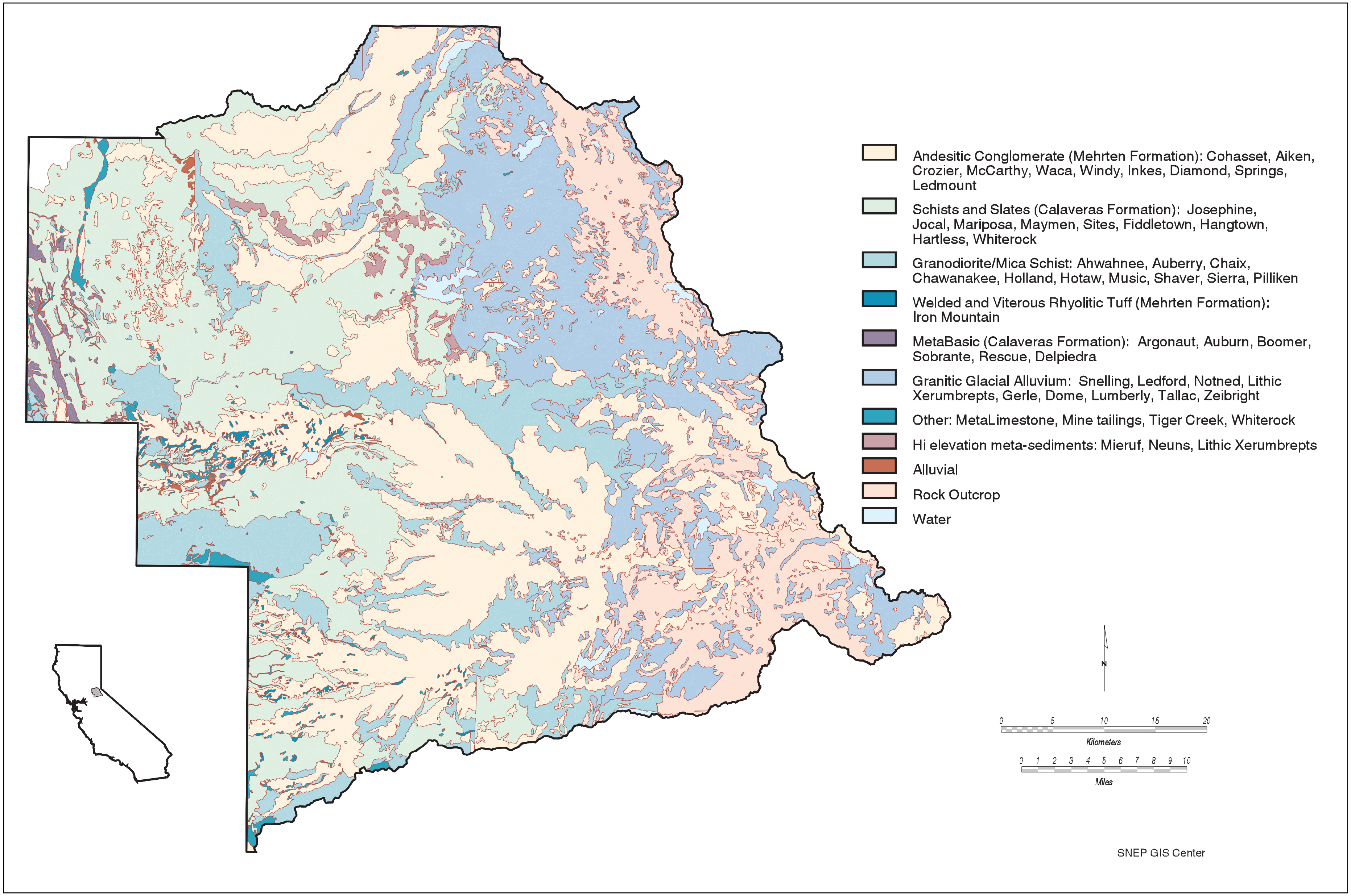

PLATE 54.1

Eldorado National Forest geology of parent material.

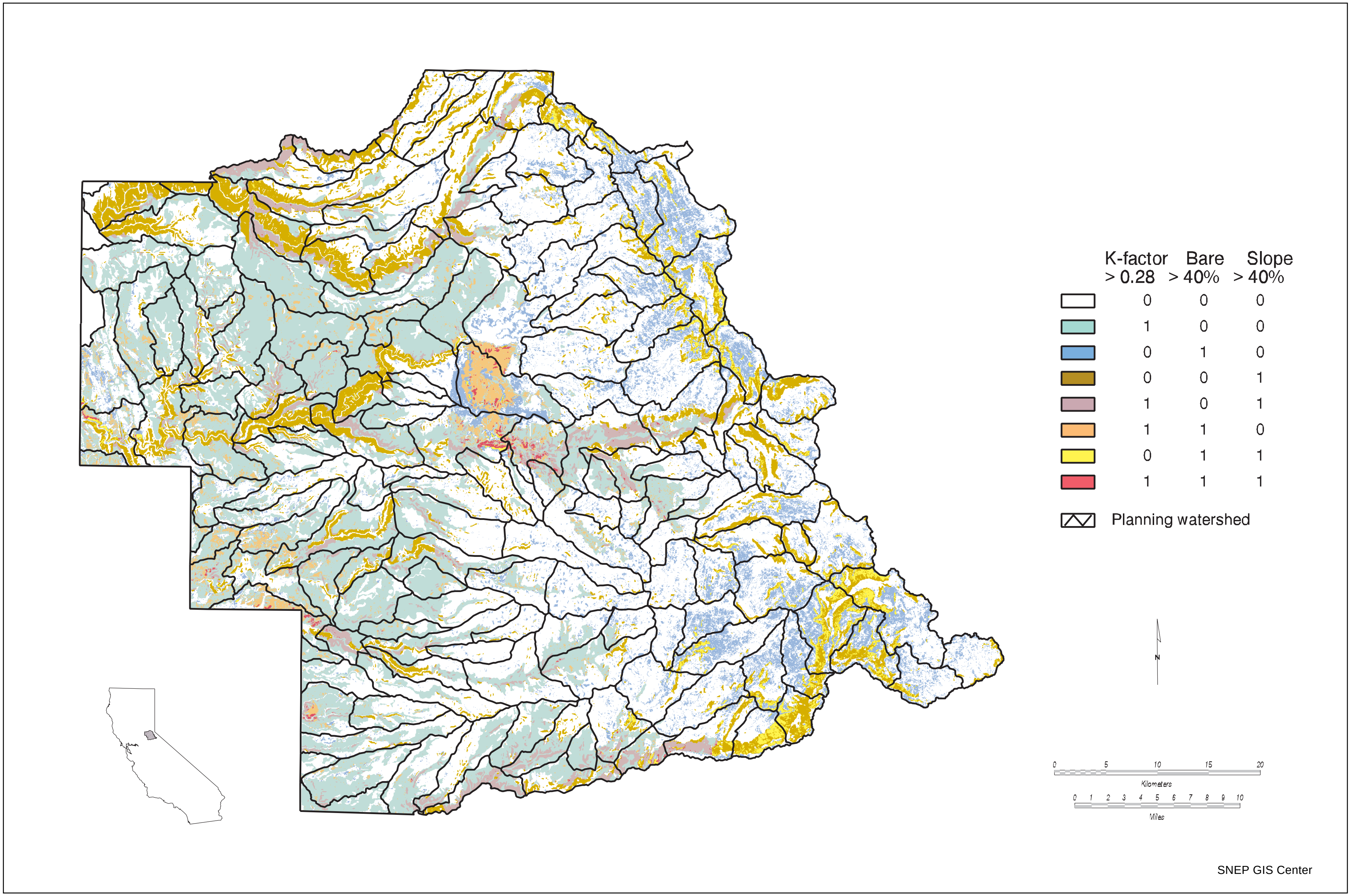

PLATE 54.2

Eldorado National Forest natural erosion potential.

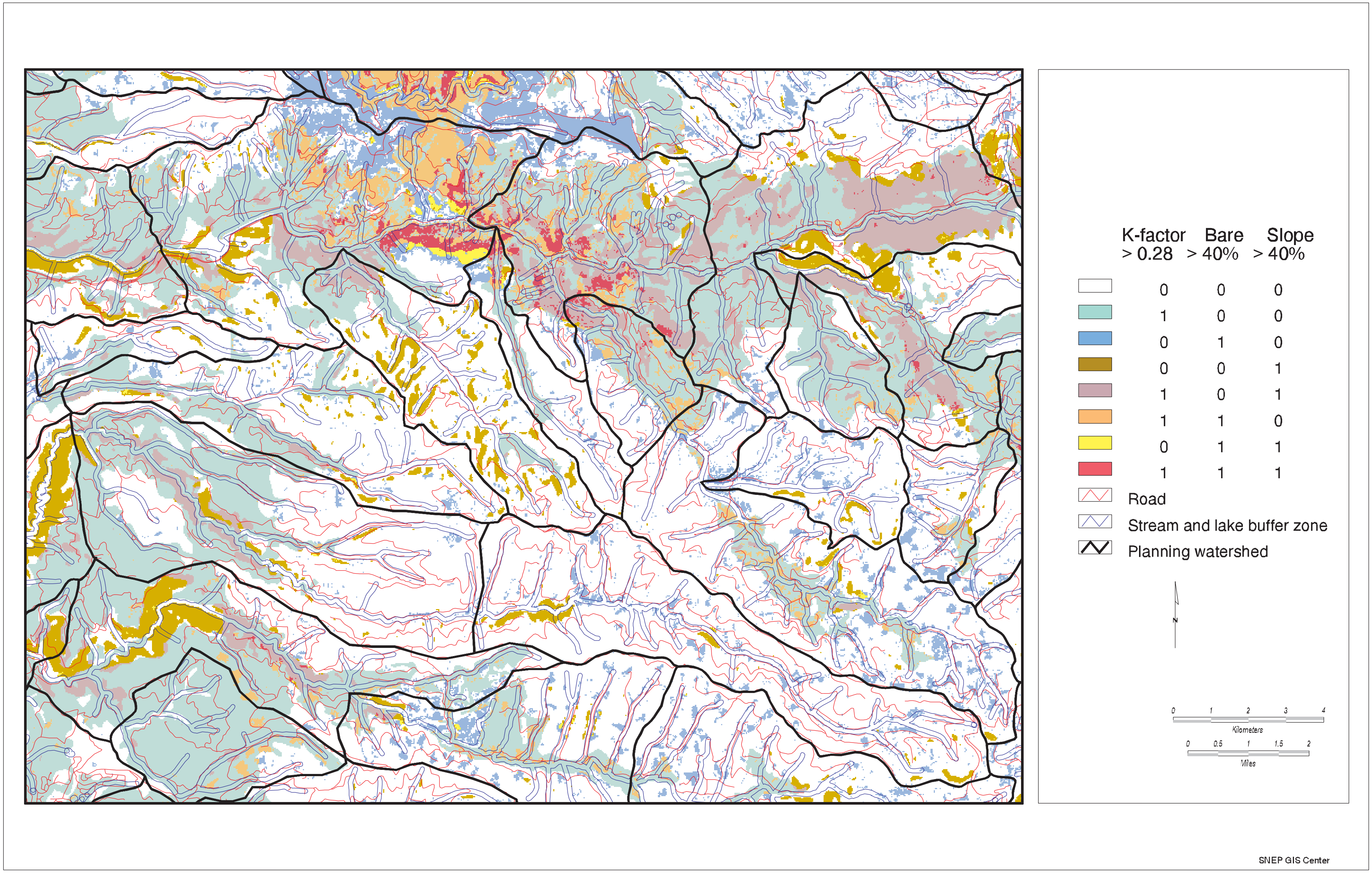

PLATE 54.3

Camp Creek area natural erosion potential.

TABLE 54.2

Fry Creek data interpretation.

Number of Cells	Total Acres	Percentage of Watershed	Soil K-Factor >0.28 (Acres)	Bare Ground >40% (Acres)	Steep Slopes >40% (Acres)	Stream Buffer (Acres)	Road in Stream Buffer (Acres)	Interpretation
28,535	6,345	100	0 *	0	0	1,123	134	6,345 acres is the watershed: 1,123 in stream buffers and 134 with roads in the buffers.
420	93	1.5	0	0	0	1	0	93 acres of stream buffer under threshold without roads.
81	18	0.3	0	0	0	1	1	18 acres of stream buffer under threshold with roads.
380	84	1.3	0	0	1 *	0	0	84 acres of slopes >40% outside of stream buffers and without roads.
17	4	0.1	0	0	1	1	0	4 acres of slopes >40% in the stream buffer.
1,363	303	4.8	0	1	0	0	0	303 acres of bare ground outside the stream buffer without roads.
14	3	0	0	1	0	1	0	3 acres of bare ground inside the stream buffer but without roads.
13	3	0	0	1	1	0	0	3 acres of bare, steep area outside the stream buffer and without roads.
8,916	1,982	31.2	1	0	0	0	0	1,982 acres of high K-factor soils outside of stream buffers or roads.
2,697	600	9.5	1	0	0	1	0	600 acres of high K-factor soils in stream buffers.
404	90	1.4	1	0	0	1	1	90 acres of high K-factor soils in stream buffers and beside roads.
5,131	1,141	18	1	0	1	0	0	1,141 acres of high K-factor and steep lands outside of stream buffers or roads.
765	170	2.7	1	0	1	1	0	170 acres of high K-factor and steep lands inside stream buffers without roads.
18	4	0.1	1	0	1	1	1	4 acres of high K-factor and steep lands inside stream buffers with roads.
2,334	519	8.2	1	1	0	0	0	519 acres of high K-factor and bare lands outside of stream buffers or roads.
420	93	1.5	1	1	0	1	0	93 acres of high K-factor and bare lands inside stream buffers without roads.
97	22	0.3	1	1	0	1	1	22 acres of high K-factor and bare lands inside stream buffers with roads.
1,358	302	4.8	1	1	1	0	0	302 acres of high K-factor, bare and steep lands outside stream buffers or roads.
112	25	0.4	1	1	1	1	0	25 acres of high K-factor, bare and steep lands inside of stream buffers without roads.
3	1	0	1	1	1	1	1	1 acre of high K-factor, bare and steep land inside of stream buffers with roads.
			4,949	1,271	1,734	1,123	134	

* “0” means no data in the “Number of Cells” column for this parameter. “1” means the number of cells shown in the “Number of Cells” column are the cells, acres, or percentage over threshold for this parameter or combination of parameters.

habitat, but only as it pertains to aquatic species. Buffers originally thought to be adequate to meet the needs of terrestrial invertebrates and to prevent or minimize sedimentation may not be adequate to maintain stream organic inputs or provide for the needs of mammals and riparian species (Kattelmann 1996). Because this study is a screening process attempting to focus the resource manager’s attention on the most acute problem areas, roads that fall within 60 meters (197 feet) of a perennial stream become the target of GIS querying. Cells fully located in the buffer between a road and stream that exceed any of the index thresholds are tagged. Where multiple thresholds are exceeded in the same cell, the magnitude of severity ensures that management attention will be focused on that location. Parameters exceeding thresholds for cells within a 60-meter buffer zone along perennial streams and adjacent to roads are calculated in the same manner as for NEP, except that the maximum potential SHI value becomes three times the total number of stream buffer cells where roads are present. Actual SHI is composed of those cells over threshold within the stream buffer where roads are present. Dividing the actual by the potential maximum, yields the percentage SHI in the same manner as percentage NEP was generated. These new values are the most critical of the process because they reflect the increased probability that sedimentation will occur at a location under specified conditions. Potential problem cells are noted and are uniquely identifiable, thus facilitating monitoring and/or mitigation. Maps of roads, stream buffers, watershed boundaries, and parameters over threshold are produced along with the tables so that graphical comparisons can be made and checked in the field. Plate 54.4 emphasizes the fact that the occurrence of cells over threshold inside stream buffers is limited. This limitation points to locations where increased sedimentation should be expected and to critical areas that should be monitored.

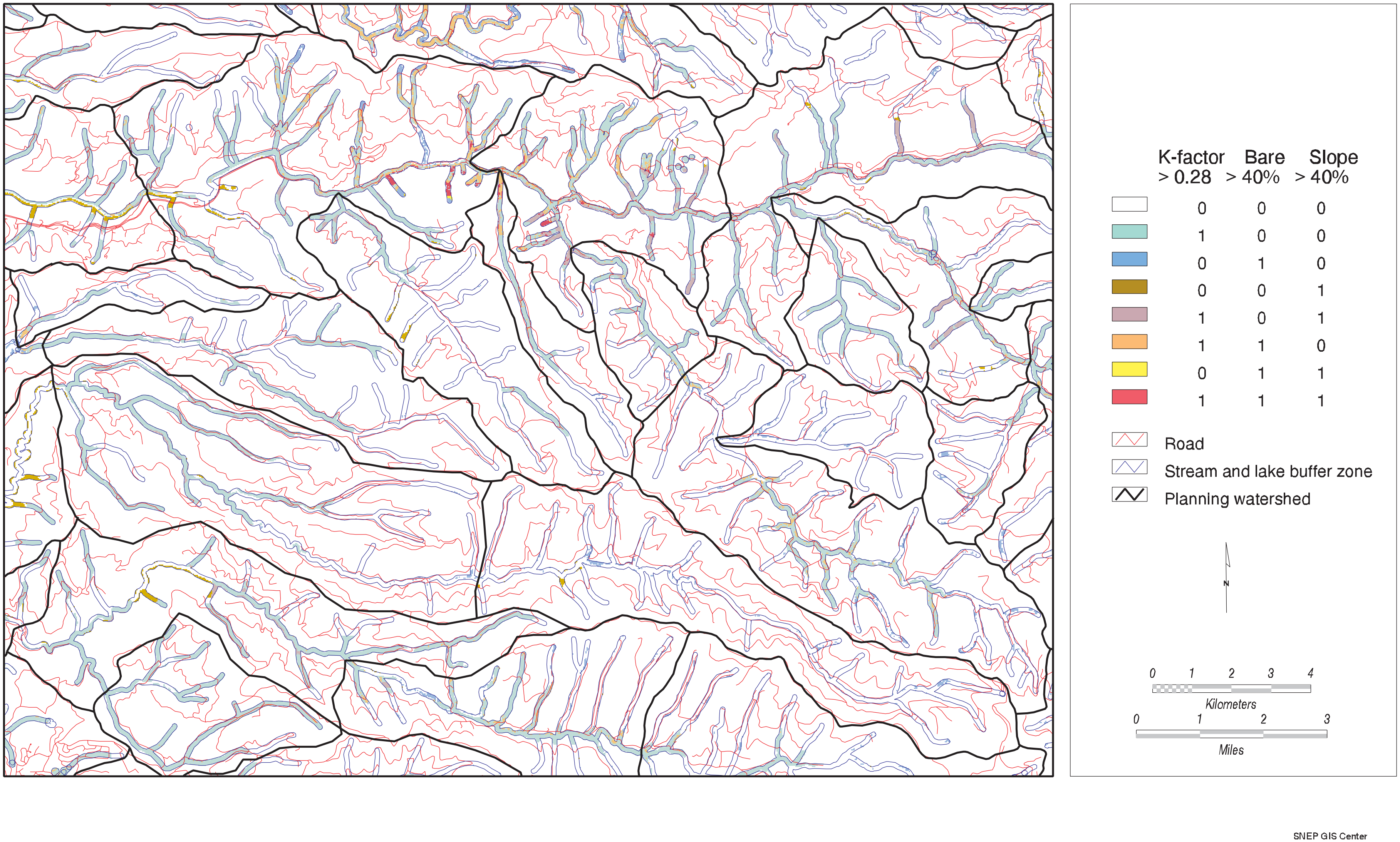

PLATE 54.4

Camp Creek area sedimentation hazard index.

Watershed Assessment Terminology

Because of data limitations for areas beyond the national forest boundaries, the application of the NEP and SHI methodology was limited to the Eldorado National Forest and to those CWPWS that were completely within the national forest. Table 54.3 features twenty-seven of 177 watersheds reviewed for this work. Differences in watershed boundaries selected by the Forest Service and Cal-Water were reconciled by consolidating Cal-Water watersheds in some cases and Forest Service watersheds in others. The consolidating process yielded 120 watersheds with adequate data for comparison. Only seventy-six of the USFS watersheds had complete data directly compatible with the model. However, all 120 watersheds had the USFS-generated natural sensitivity index (NSI). Designed by Kuehn in 1989 for cumulative watershed effects analysis on the ENF, this indexing system considers both hillslope and in-channel hydrologic and erosional processes. Soils, stream channel conditions, geomorphic instability, drainage density, and precipitation regimes are all part of the NSI calculation. NSI as seen in table 54.4 is used to generate a watershed's threshold of concern (TOC) (U.S. Forest Service, 1987). TOC relates to the percent of equivalent roaded acres (ERA), which is a watershed ranking by the amount and type of land disturbance within a watershed. TOC for a watershed is determined by the NSI number, where less than 15 is very low and greater than 65 is very high. For watersheds with very low NSI numbers, the TOC will range from 18% to 20% ERA, meaning that 20% of the watershed may be disturbed before significant cumulative effect occurs. Likewise, watersheds with very high NSI numbers have lower TOCs, and as little as 10% ERA may trigger significant CWE.

RESULTS AND DISCUSSIONS

Model Comparison with USFS Outputs

One of the highest Forest Service NSI and TOC rankings is that of the 6,346-acre Fry Creek watershed (see plate 54.3 and table 54.3). A tributary of the South Fork of the American River, much of its ground cover was burned in the 1993 Cleveland fire. It has steep slopes and highly detachable soils. The NSI is 183 and the percentage TOC is 138%. A TOC of 138% indicates that this watershed is significantly over the USFS threshold and that further unmitigated disturbance may result in considerable harm to the ecosystem. This model calculated Fry Creek as one of its highest risk watersheds, with NEP and SHI ratings of 41.7% and 35.5%, respectively. The USFS erosion hazard rating (EHR) risk number for this watershed, as seen in the seventh column of table 54.3, is 5: extreme.

Model Construction Time and Proposed Uses

The model yields a relative ranking for each watershed without extensive field surveys and could be used to guide future mitigation activity. Advantages of the model include lower dollar costs to produce, objective generation, capacity to be easily updated, responsiveness to changes in elevation and precipitation conditions, and reduced data corruption because minimal staff (one or two individuals) are required to process data.

After the soil database was constructed, 177 Cal-Water planning watersheds were reviewed and 134 analyzed for natural erosion potential and sedimentation hazards using approximately ten days of GIS and analysis time. Positive correlation with the Eldorado National Forest's natural sensitivity index and equivalent roaded acres methodology provides significant encouragement to continue refining this model and expanding its application to other portions of the Sierra Nevada Ecosystem Project study area. NEP and SHI rankings may be modified by testing mitigation alternatives, which include the surfacing and abandonment of road segments in areas over erosion parameter threshold.

Correlation Comparisons

As seen in table 54.5 the correlation coefficients (r) are positive when comparing the Forest Service indexes: USFS's NSI, ERA, and TOC and this model's NEP and SHI. Using all 120 comparable watersheds, the correlation between NSI and NEP is 0.54. Between TOC and SHI, with data from seventy-six watersheds, it is 0.44, and between ERA and SHI it is 0.34. The model has only been run once; hence ground truthing to better calibrate its predictions will continue. Percentage roaded acres (RdAcs) in this model is not the equivalent of ERA because ERA includes all cumulative logging disturbance and RdAcs is only the 30 meters of the roadway. Likewise, stream buffer acres (StBufAc) include only the percentage of the watershed where roads are present inside the stream buffer. Finding that 54% of the variation in NSI ranking is explained by the variation in NEP is encouraging, considering the difference in these methodologies. Improving calibration for large areas of exposed bedrock, accounting for precipitation isohyets and their influence on areas of high rain-on-snow potential, and change detection analysis should improve the correlation between the USFS assessment method and this model. The ERA method of analysis is likewise an evolving technique requiring large commitments of personnel time in both field and disturbance history research. Greater opportunity for human bias has led to the objectivity of the ERA method to be questioned.

Model-Directed Mitigation

After reviewing the results of the screening analysis and making an on-the-ground inspection of potential hazards, one of

TABLE 54.3

Twenty-seven Eldorado National Forest watersheds with the highest sedimentation hazard indexes and their corresponding natural sensitivity index and threshold of concern rankings.

Cal-Water Planning Watershed ID Number	Cal-Water Watershed Name	Cal-Water Planning Watershed Acres	Natural Sensitivity Index	Percentage Threshold of Concern	Percentage Equivalent Roaded Acres	Erosion Hazard Rating Number	Percentage Natural Erosion Potential	Percentage Sedimen-tation Hazard Index	Percent-age Roaded Acres	Percentage - Roaded Acres Inside Stream Buffers
514.33021	Peavine Creek	11,510	60	125.0	15	5	40.9	38.6	10.5	11.4
514.35021	Fry Creek	6,346	183	138.0	13.8	5	41.7	35.5	9.1	11.9
514.32010	Gaddis Creek	8,684	81	106.0	10.6	5	35.2	34.6	8.2	9
532.60051	Beaver Creek	2,464	95	100.0	10	5	31.7	34.6	8.2	9.5
514.33035	Camp Seven	4,248	291	70.0	7	3	32.4	34.4	6.1	5.3
514.32012	Brush Creek	5,132	37	36.4	5.1	2	36.6	34.0	10.2	7.7
532.23043	Clear Creek	2,896	34	61.3	9.8	3	28.1	32.2	10.3	14.1
514.33030	Little Silver Creek	8,604	28	68.1	10.9	3	30.6	32.0	9.6	11.3
514.35050	Twenty-Five Mile Cyn	10,972	138	129.0	12.9	5	33.6	31.6	9.6	10.8
532.60061	W Panther Creek	5,853	79	104.0	10.4	5	26.1	30.2	11.3	9.9
532.23042	Middle Butte	2,925	160	53.0	5.3	2	31.1	29.8	6.2	3.2
514.36033	Middle Creek	4,735	119	50.0	5	3	24.5	29.8	7.0	6.9
514.32022	Whaler Creek	10,209	91.3	62.0	6.2	3	29.7	29.4	11.5	11
532.23033	North Canyon	3,541	25	23.1	3.7	1	29.5	28.8	10.0	15.3
514.32011	Slab Creek	5,493	114	43.0	4.3	2	32.3	27.9	11.0	8.6
532.23062	Clear Creek	6,840	28	50.0	8	2	28.0	27.7	13.1	14.5
514.32031	Bear Creek	5,358	59	68.3	8.2	3	28.1	27.4	12.6	16
514.32013	Slab Creek Res	5,723	174	51.0	5.1	2	28.7	26.8	9.8	6.1
514.35022	Mill Creek	2,178	61	117.5	14.1	5	11.5	24.9	8.6	8.1
514.35051	Grays Canyon	8,308	173	51.0	5.1	2	31.2	24.6	9.0	5.7
514.43033	Zero Spring	8,212	220	30.0	3	2	34.8	24.5	6.0	4.2
514.32015	Iowa Canyon	5,107	41	95.0	13.3	4	18.2	24.5	14.2	10.9
514.32021A	AWS1	13,502	94	34.0	3.7	2	25.1	24.4	10.3	0
532.24012	Cat Creek	5,655	93	138.0	13.8	5	14.4	23.9	10.7	13.8
532.23032	Van Horn Creek	7,516	77	64.0	6.4	3	26.5	23.8	10.2	12.3
514.35052	Soldier Creek	3,414	52	103.3	12.4	5	17.6	23.5	9.3	13.4
532.23051	Camp Creek	10,140	92	66.0	6.6	3	29.9	23.3	7.4	3.9

TABLE 54.4

Relationship of natural sensitivity index to equivalent roaded acres and threshold of concern (from Carlson and Christiansen 1993).

NSI	Sensitivity	TOC
<15	Very low	18–20% ERA
16–35	Low	16–18% ERA
36–50	Moderate	14–16% ERA
51–65	High	12–14% ERA
>65	Very high	10–12% ERA

the first questions to be asked is “What are the mitigation opportunities?” It is not possible to change a soil’s K-factor, but one can consider abandoning or surfacing roads when they are located adjacent to streams on highly detachable soils, especially where they are combined with steep slopes and bare ground. In the Fry Creek example (table 54.2), 603 cells, totaling 134 acres or sixty-one hectors of roads, are present within stream buffers and represent opportunities for possible CWE mitigation. Being able to locate these cells using a GPS, portable computer, and GIS programs provides a means for immediate optimization of mitigation alternatives based on the recalculation of SHI. Some high-risk cells will become candidates for road abandonment, road surfacing, culvert replacement, or fill-slope ripraping. The current cumulative condition of the watershed can be evaluated and improved as soon as mitigation has been completed to reduce risks. Abandoning a portion of road within a stream buffer or on steep bare ground where the soils are highly detachable reduces the denominator in the formula equation, thereby reducing the percentage SHI. Reducing the risk factors will also reduce the percentage of the watershed exceeding thresholds, and, if it does not improve the watershed’s ranking relative to others, it will at least allow for additional management to take place without excessive risk.

Other opportunities to influence the NEP or SHI are available through planting, seeding, and/or mulching of bare areas. The Fry Creek watershed has 5,716 cells, 1,271 acres, or 578 hectors that could be considered for this treatment. The number includes all those cells or combinations of cells that are bare and exceed other thresholds. It includes many areas that are already planted in trees but are not yet tall enough to provide a closed canopy. Bare rock outcrops and heavily grazed meadows also give the spectral signature of bare ground or bare ground covered with nongreen vegetation such as logging slash or litter. Some of these conditions cannot be mitigated or may not need treatment. After mitigation, however, treated cells are deducted from the list, and the NEP and SHI indexes are recalculated. Resource managers may choose to optimize both environmental and economic investment strategies by locating those areas that have the greatest impact on cumulative watershed effects and selecting the mitigation that is most cost and environmentally effective. Thinking of this as an environmental accounting system permits one to allocate resources to those projects that have the most immediate impact on the net reduction of cumulative effects.

TABLE 54.5

Correlation coefficients, *r*, for the NEP and SHI model output.

	NSI	ERA	TOC
NEP	0.54	0.19	0.33
SHI	0.43	0.34	0.44
RdAcs	–0.12	0.47	0.42
StBufAc	–0.29	0.37	0.24

CONCLUSIONS

Need for Public-Private Cooperation

One of the most important assessment findings of the SNEP Hydrology Group is the absence of standardized tools that provide resource managers with the information they need for sound economic and environmental decision making. To make the Sierra Nevada ecosystem sustainable, both public and private landowners must be able to exchange information about their individual activities accurately, quickly, and in similar formats. Sustainability of forest ecosystems in both the eastern and western United States depends on understanding the “current cumulative condition.” In order to gain this understanding at a regional scale, one must have information on what resource elements are present and how are they distributed, regardless of ownership.

Thirty-six percent of the nearly twenty-nine million acres in the SNEP study area are privately owned. These private lands are relatively evenly dispersed in “mixed ownership watersheds.” The natural boundaries of many mixed ownership watersheds often exceed the administrative boundaries of the national forests and divide the watershed for analysis purposes. As an example, there might be one-third of the watershed inside the national forest, two-thirds outside, half of which is held by large landowners and half held in small lots for residential use or investment. While each landholding group may have different management plans, all agencies and private operators need a standardized database in order to calculate the combined impacts of their land use histories and from which to project their combined future activities.

Model Expansion and Improvement

As standardized and integrated soils databases are completed for other portions of the Sierra Nevada, and as DEMs of higher resolution become available, a Sierra-wide NEP and SHI analysis could be completed and reanalyzed periodically to evaluate the impacts of residential development, fire, timber harvest, and other regionally important phenomena that can be observed from space. Although this model will continue to be evaluated and validated, effects of additional elements such as climate, rain on snow, and geology will be tested to improve model performance. High-elevation basins are important and sensitive even if unmanaged; however, their contribution to the sediment load is not potentially as high as that of lower-elevation areas that are heavily managed. Therefore the problem of separating bare rock outcrops from bare exposed soil will be an important element of future NEP models.

Adjudication of “Disturbance Rights” in CWE Limited Watersheds

An accurate indexing methodology is a valuable tool when allocating resources for watershed improvement or adjudicating “disturbance rights” between landowners. Predicting the erosional potential for a given unit area of land is the objective of this methodology; it is intended to index current cumulative condition for individual planning watersheds relative to their neighbors.

The adjudication of logging rights has not yet been implemented in mixed ownership watersheds. As watersheds become “cumulative effects limited,” or over the threshold of concern, to the extent that management operation must be modified, this model will provide the basis for selection of mitigation projects as well as locate areas to be avoided or managed with more informed sensitivity.

With these tools, decisions about road location, road abandonment, skid trail layout, recreation, and grazing practices may be reviewed on local or regional scales and provide better information for balancing ecosystem health, cumulative effects, and human need in order to maintain all systems in sustainable condition.

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